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Svedberg et al.

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(54) **PARTICLE ACCELERATORS HAVING EXTRACTION FOILS**

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H05H 7/10 (2006.01)

(52) **U.S. Cl.**
CPC ***H05H 7/10*** (2013.01); ***H05H 13/005*** (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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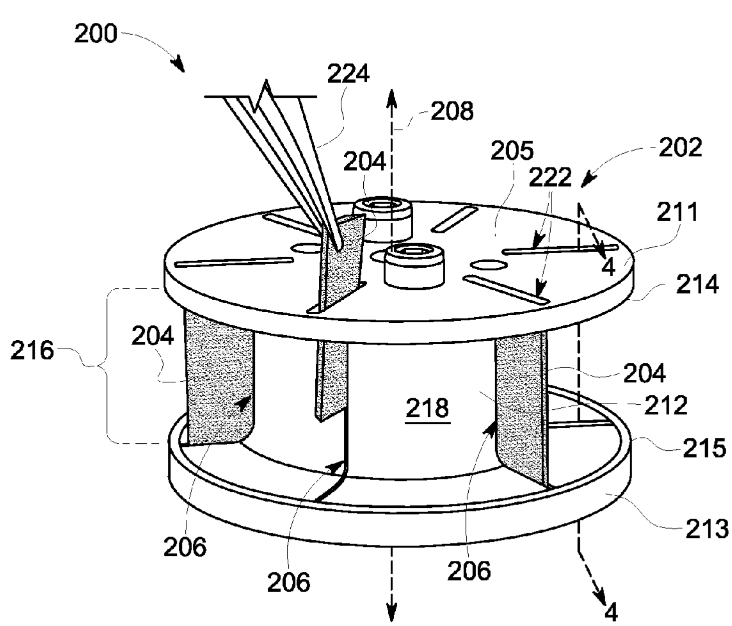
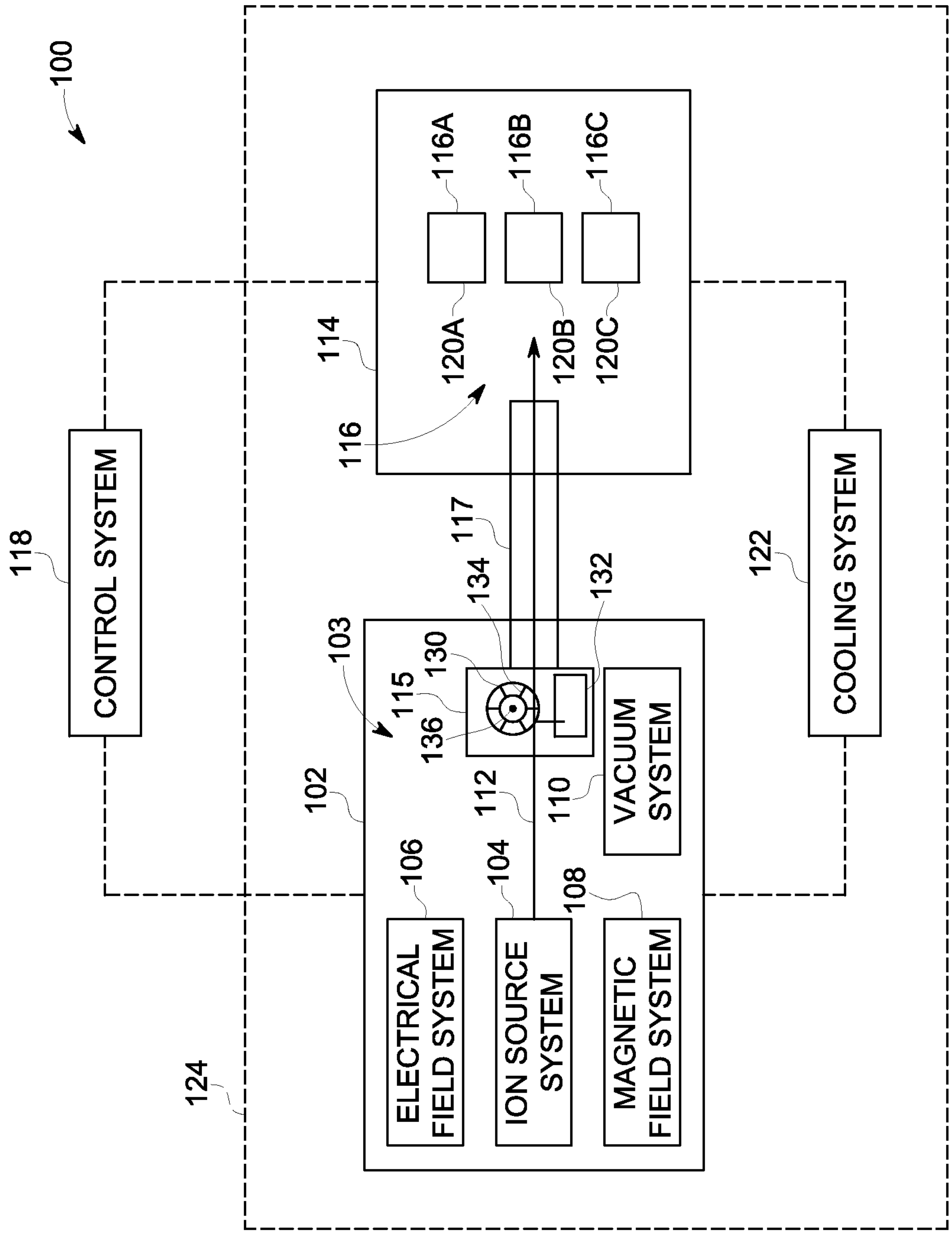
(57) **ABSTRACT**

A particle accelerator including an electrical field system and a magnetic field system that are configured to direct a particle beam of charged particles along a designated path within an acceleration chamber. The particle accelerator also includes a foil holder having a beam window and a positioning slot that at least partially surrounds the beam window. The positioning slot is dimensioned to hold an extraction foil such that the extraction foil extends across the beam window and into the path of the charged particles. The positioning slot is defined by interior reference surfaces that face the extraction foil and retain the extraction foil within the positioning slot. The reference surfaces permit the extraction foil to move relative to the reference surfaces when the particle beam is incident on the extraction foil.

20 Claims, 8 Drawing Sheets





100
CONTROL SYSTEM
118
COOLING SYSTEM
122
124
114
116
116A
116B
116C
120A
120B
120C
117
103
102
130
132
134
115
136
112
110
VACUUM SYSTEM
106
104
108
ELECTRICAL FIELD SYSTEM
ION SOURCE SYSTEM
MAGNETIC FIELD SYSTEM

FIG. 1

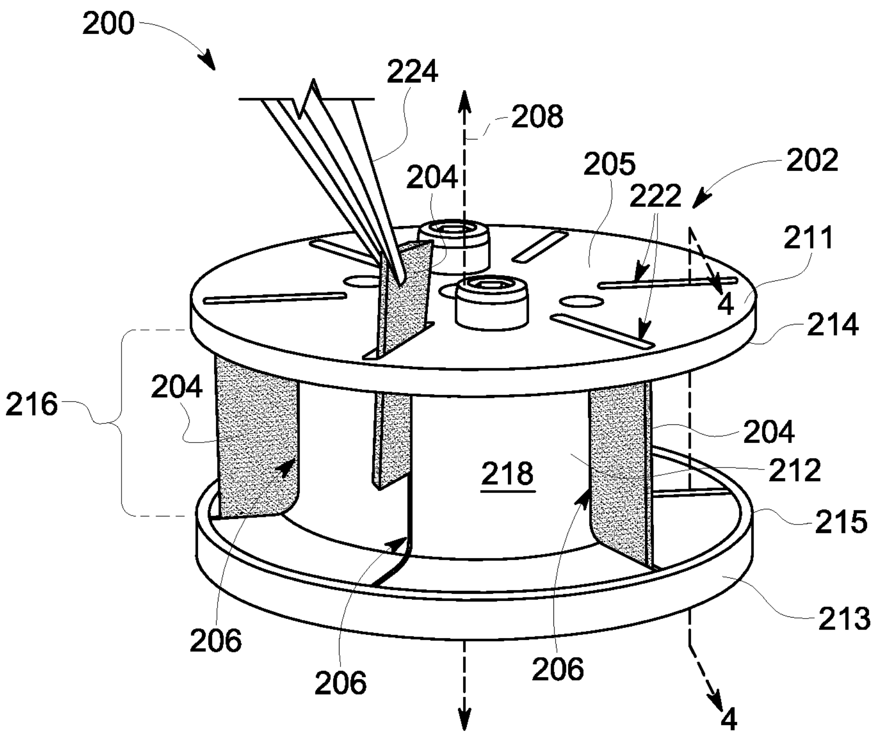

200
224
208
204
205
202
222
211
4
214
216
204
204
218
212
215
213
206
206
206
4

FIG. 2

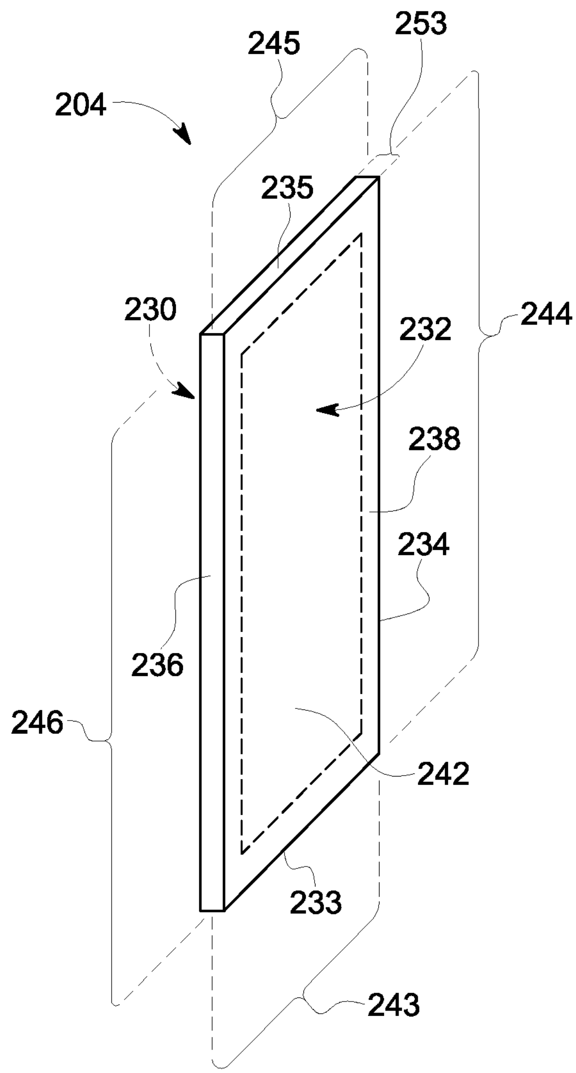


FIG. 3

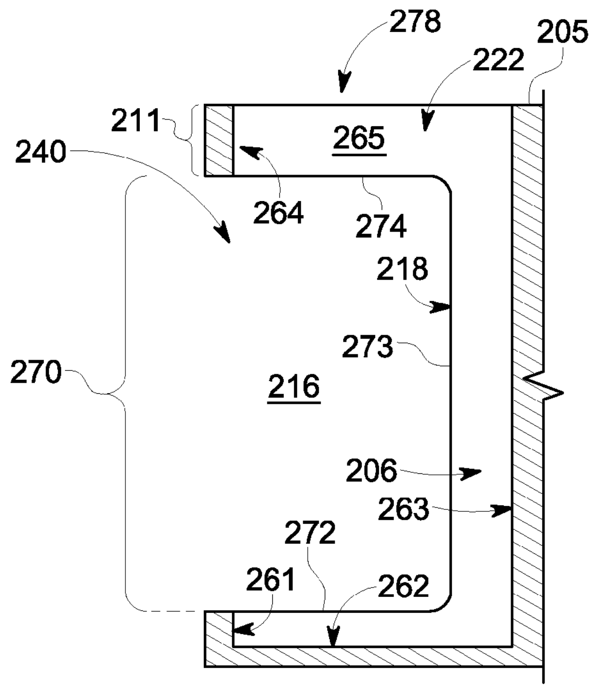

278
205
222
211
265
240
264
274
218
273
270
216
206
263
272
261
262

FIG. 4

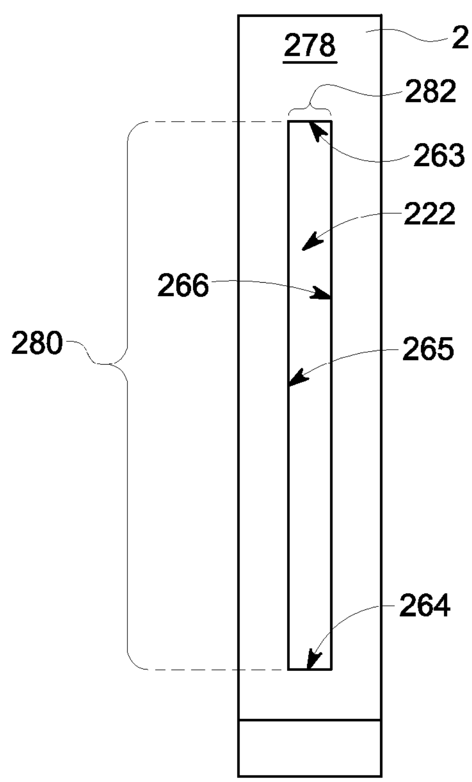

278
211
282
263
222
266
280
265
264

FIG. 5

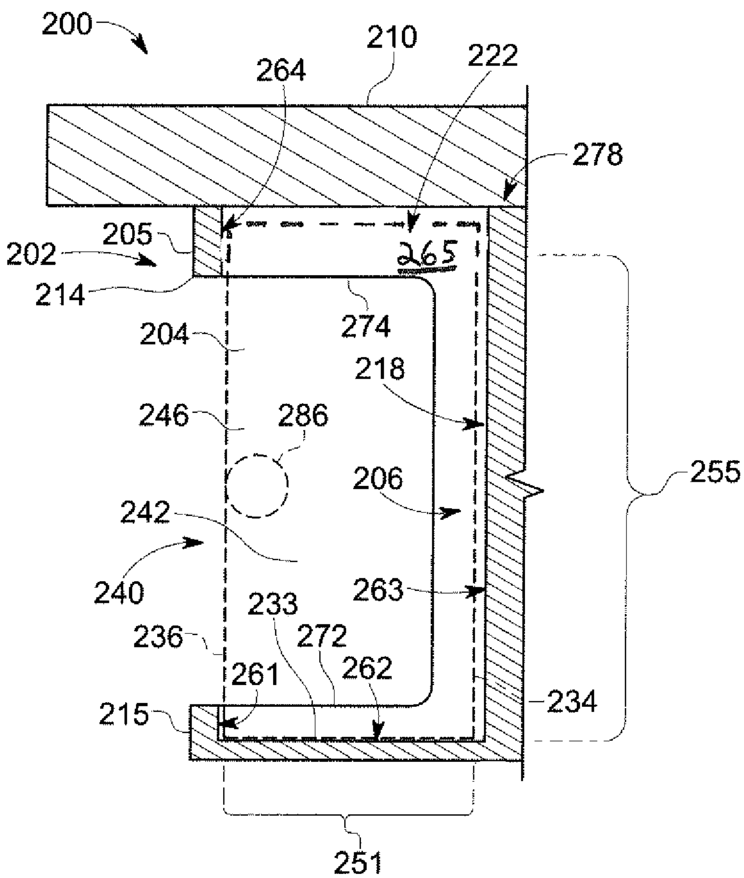

200
210
222
264
278
205
202
265
214
274
204
218
246
286
206
242
240
263
233
236
272
261
262
215
234
255
251

FIG. 6

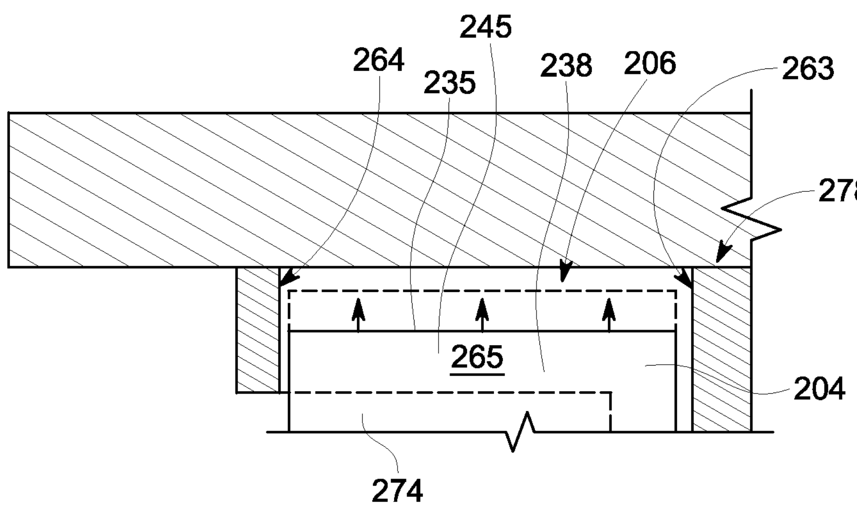


FIG. 7

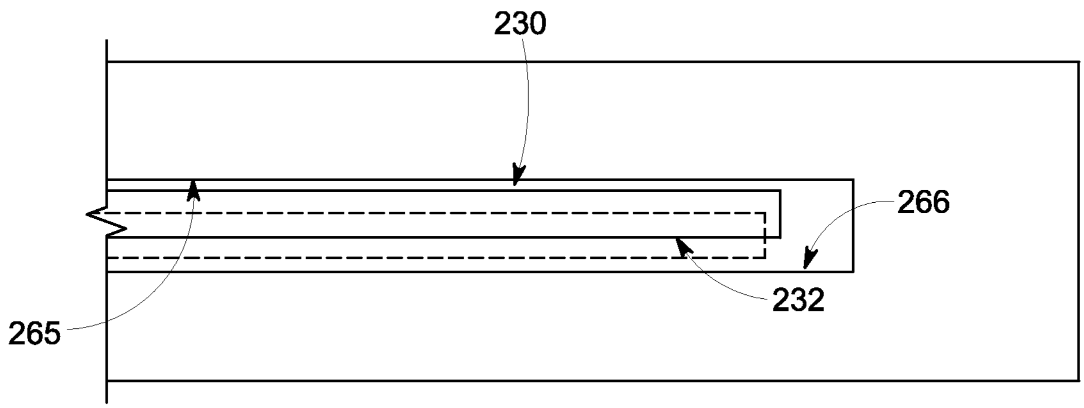


FIG. 8

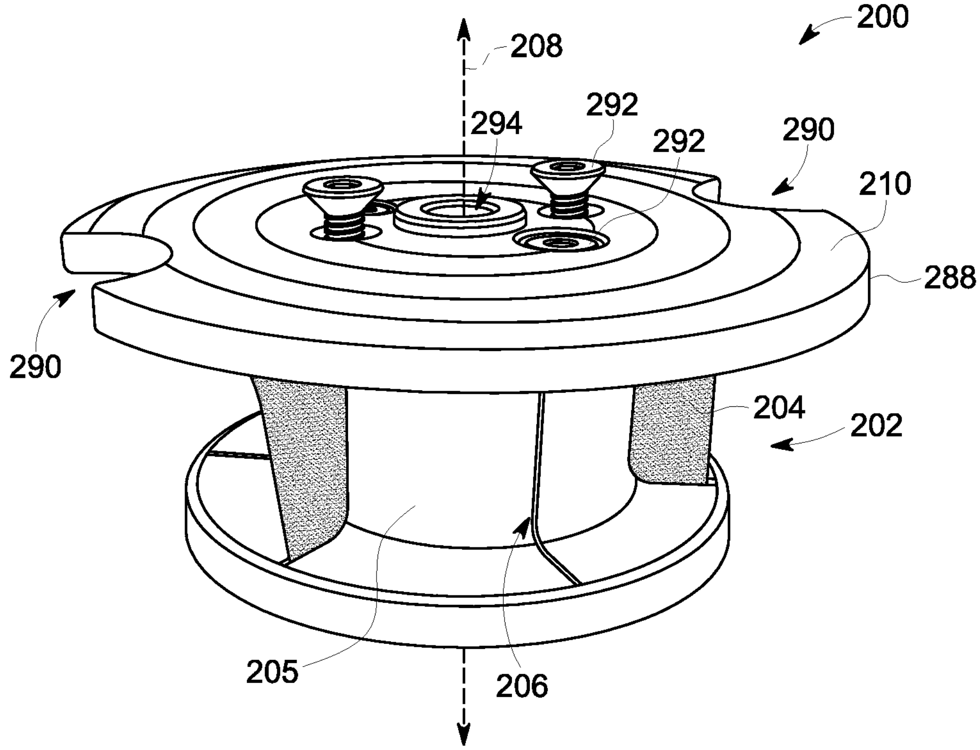


FIG. 9

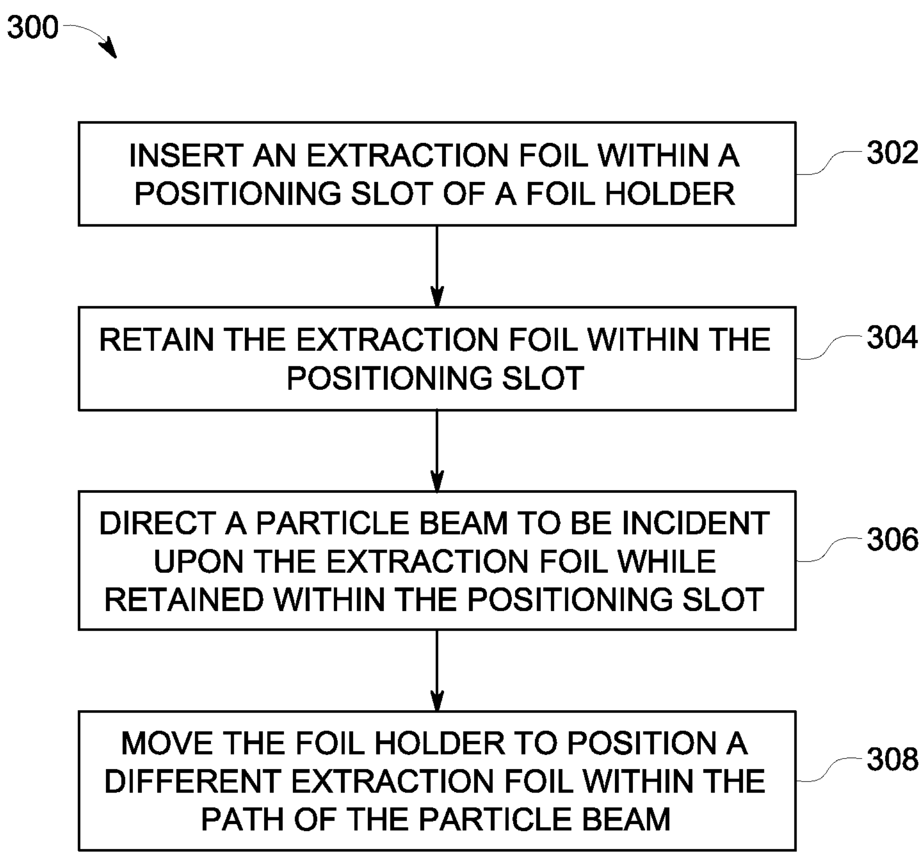

300
INSERT AN EXTRACTION FOIL WITHIN A POSITIONING SLOT OF A FOIL HOLDER
302
RETAIN THE EXTRACTION FOIL WITHIN THE POSITIONING SLOT
304
DIRECT A PARTICLE BEAM TO BE INCIDENT UPON THE EXTRACTION FOIL WHILE RETAINED WITHIN THE POSITIONING SLOT
306
MOVE THE FOIL HOLDER TO POSITION A DIFFERENT EXTRACTION FOIL WITHIN THE PATH OF THE PARTICLE BEAM
308

FIG. 10

PARTICLE ACCELERATORS HAVING EXTRACTION FOILS

BACKGROUND OF THE INVENTION

Various embodiments described herein relate generally to particle accelerators, and more particularly to particle accelerators having extraction foils for stripping electrons from charged particles.

Particle accelerators, such as cyclotrons, may have various industrial, medical, and research applications. For example, particle accelerators may be used to produce radioisotopes (also called radionuclides), which have uses in medical therapy, imaging, and research, as well as other applications that are not medically related. Systems that produce radioisotopes typically include a cyclotron that has a magnet yoke surrounding an acceleration chamber. The cyclotron may include opposing pole tops that are spaced apart from each other. Electrical and magnetic fields may be generated within the acceleration chamber to accelerate and guide charged particles along a spiral-like orbit between the poles. To produce the radioisotopes, the cyclotron forms a particle beam of the charged particles and directs the particle beam out of the acceleration chamber and toward a target system having a target material. The particle beam is incident upon the target material thereby generating radioisotopes.

Known cyclotrons direct the charged particles so that the charged particles are incident upon an extraction foil. For example, the extraction foil may be positioned at an outer edge of the spiral-like orbit so that the charged particles reach a predetermined speed prior to being incident upon the extraction foil. When the charged particles hit the extraction foil, the foil strips electrons from the charged particles causing the particles to change polarity and thereby project out of the acceleration chamber.

In conventional cyclotrons that use extraction foils, the foils are held by a frame within the path of the charged particles. At least two edges of the extraction foil may be secured to the frame (e.g., through clamping or the like) such that the edges have fixed positions with respect to the frame. Another edge of the extraction foil may be exposed and positioned within a path of the charged particles. When the charge particles are incident upon the extraction foil, the extraction foil experiences a significant increase in temperature, such as 750 K or more. The significant temperature change causes the foil to change in size (e.g., expand). The size change is based on the material of the foil and the coefficient of thermal expansion of the material.

Such extraction foils are susceptible to failure. The portions of the extraction foil that are secured by the frame may experience stresses caused by the clamping forces of the frame. In addition, the portion of the extraction foil that receives the charged particles experiences a very significant temperature change. Moreover, the change in size caused by the temperature change creates additional stresses on the extraction foil because the frame holds the edges in fixed positions. More specifically, when the edges have fixed positions, the extraction foil is incapable of expanding or contracting within a plane. Instead, portions of the extraction foil may buckle and/or stretch. Accordingly, the above stresses may cause damage to the extraction foil that eventually leads to foil failure. Although damaged extraction foils may be replaced, such procedures have undesirable consequences. First, the procedure for replacing extraction foils increases radiation exposure to personnel. Second, during the replacement procedure, the cyclotron is not in operation.

Accordingly, there is a need for a particle accelerator that increases the lifetime operation of the extraction foils thereby reducing the frequency of foil replacement.

BRIEF DESCRIPTION OF THE INVENTION

In one embodiment, a particle accelerator is provided that includes an electrical field system and a magnetic field system that are configured to direct a particle beam of charged particles along a designated path within an acceleration chamber. The particle accelerator also includes a foil holder having a beam window and a positioning slot that at least partially surrounds the beam window. The positioning slot is dimensioned to hold an extraction foil such that the extraction foil extends across the beam window and into the path of the charged particles. The positioning slot is defined by interior reference surfaces that face the extraction foil and retain the extraction foil within the positioning slot. The reference surfaces permit the extraction foil to move relative to the reference surfaces when the particle beam is incident on the extraction foil.

In another embodiment, an extraction system for removing electrons from charged particles is provided. The extraction system includes a foil holder having a beam window and a positioning slot that at least partially surrounds the beam window. The positioning slot is dimensioned to hold an extraction foil such that the extraction foil extends across the beam window. The positioning slot is defined by interior reference surfaces that face the extraction foil and retain the extraction foil within the positioning slot. The reference surfaces are dimensioned to permit the extraction foil to move relative to the reference surfaces when the charged particles are incident on the extraction foil.

In yet another embodiment, a method of operating a particle accelerator is provided. The method includes retaining an extraction foil within a positioning slot. The extraction foil has at least one edge portion that defines a profile of the extraction foil and a body portion that is exposed for receiving a particle beam. The positioning slot is defined by interior reference surfaces that face the edge portion wherein at least one of the reference surfaces directly engages the extraction foil. The method also includes directing the particle beam to be incident upon an extraction foil. The edge portion of the extraction foil is permitted to move relative to the reference surfaces.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram of a particle accelerator in accordance with one embodiment.

FIG. **2** is an enlarged perspective view of a holder body of a foil holder that may be used with the particle accelerator of FIG. **1**.

FIG. **3** is a perspective view of an extraction foil that may be used by one or more embodiments described herein.

FIG. **4** is a cross-section of the foil holder of FIG. **2** illustrating dimensions of a positioning slot for holding an extraction foil.

FIG. **5** is an enlarged view of a slot opening that provides access to the positioning slot.

FIG. **6** is a cross-section of the foil holder of FIG. **2** showing the extraction foil retained within the positioning slot.

FIG. **7** is an enlarged view of the cross-section of the foil holder illustrating movement of the extraction foil within the positioning slot when charged particles are incident on the extraction foil.

FIG. **8** is an enlarged view of the slot opening illustrating movement of the extraction foil within the positioning slot when charged particles are incident on the extraction foil.

FIG. **9** is a perspective view of the foil holder in which a holder cover is mounted to the holder body.

FIG. **10** is a flowchart illustrating a method of operating a particle accelerator in accordance with one embodiment.

DETAILED DESCRIPTION OF THE INVENTION

Embodiments described herein include isotope productions systems, particle accelerators, and extraction systems or devices of the same. Particular embodiments include foil holders that may be used with extraction systems of a particle accelerator. The foil holder may be configured to retain one or more extraction foils that are used to strip electrons from charged particles. The foil holder may retain the extraction foils within positioning slots. The extraction foils in some embodiments may not be tightly gripped or clamped by the foil holder thereby reducing unwanted stresses on the extraction foil. The extraction foil may be positioned by the foil holder to extend across a path taken by charged particles during operation of the particle accelerator so that the charged particles are incident on the extraction foil. During the stripping process, thermal energy may be generated within the extraction foil causing the extraction foil to change size and/or shape. Embodiments described herein may have positioning slots that are dimensioned to permit the extraction foil to change in size and/or shape while maintaining the position of the extraction foil relative to the charged particles (or particle beam). Such embodiments may increase the lifetime operation of the extraction foils so that fewer replacement procedures are required.

As used herein, an element or step recited in the singular and proceeded with the word “a” or “an” should be understood as not excluding plural of said elements or steps, unless such exclusion is explicitly stated. Furthermore, references to “one embodiment” are not intended to be interpreted as excluding the existence of additional embodiments that also incorporate the recited features. Moreover, unless explicitly stated to the contrary, embodiments “comprising,” “including,” or “having” an element or a plurality of elements having a particular property may include additional such elements that do not have that property.

FIG. **1** is a block diagram of an isotope production system **100** formed in accordance with one embodiment. The system **100** includes a particle accelerator **102** that has several subsystems including an ion source system **104**, an electrical field system **106**, a magnetic field system **108**, and a vacuum system **110**. The particle accelerator **102** may be, for example, a cyclotron or, more specifically, an isochronous cyclotron. The particle accelerator **102** may include an acceleration chamber **103**. The acceleration chamber **103** may be defined by a housing or other portions of the particle accelerator and is configured to have an evacuated state during operation. The particle accelerator shown in FIG. **1** has at least portions of the sub-systems **104**, **106**, **108**, and **110** located in the acceleration chamber **103**.

During use of the particle accelerator **102**, charged particles are placed within or injected into the acceleration chamber **103** of the particle accelerator **102** through the ion source system **104**. The magnetic field system **108** and the electrical field system **106** generate respective fields that cooperate in producing a particle beam **112** of the charged particles. The charged particles are accelerated and guided within the acceleration chamber **103** along a predetermined or designated path. In cyclotrons, for example, the designated path may be a spiral-like orbit.

During operation of the particle accelerator **102**, the acceleration chamber **103** may be in a vacuum (or evacuated) state and experience a large magnetic flux. For example, an average magnetic field strength between pole tops in the acceleration chamber **103** may be at least 1 Tesla. Furthermore, before the particle beam **112** is created, a pressure of the acceleration chamber **103** may be approximately 1×10^{-7} millibars. After the particle beam **112** is generated, the pressure of the acceleration chamber **103** may be approximately 2×10^{-5} millibar.

Also shown in FIG. **1**, the system **100** has an extraction system **115** and a target system **114** that includes a target material **116**. In some embodiments, the particle accelerator **102** and the target system **114** may be enclosed or housed within a single system housing **124** (indicated by broken lines. However, the target system **114** may be separate from the particle accelerator **102** in other embodiments. The extraction system **115** may be positioned at an edge of the spiral-like orbit. The extraction system **115** includes a foil holder **130** and a rotating motor **132** that is operably coupled to the foil holder **130**. The foil holder **130** is illustrated as a revolving device or carousel, but other foil holders may be used in other embodiments. The foil holder **130** is configured to hold one or more extraction foils **134** (a plurality of extraction foils **134** is shown in FIG. **1**). The rotating motor **132** is configured to selectively move the foil holder **130** about an axis of rotation **136** to designated rotational positions. For example, the foil holder **130** may be rotated so that different extraction foils **134** are incident on the charged particles. The rotating motor **132** may be, for example, an electromechanical motor that is driven by piezoelectric elements as set forth in U.S. application Ser. No. 12/977,208, which is incorporated by reference in its entirety.

As shown, the target system **114** is positioned adjacent to the particle accelerator **102**. To generate isotopes, the charged particles are directed by the particle accelerator **102** to be incident on the extraction foil **134** of the extraction system **115**. For some embodiments, when the charged particles (e.g., negative hydrogen ions) are incident upon the extraction foil **134**, electrons of the charged particles may be stripped from the charged particle thereby changing the charge of the particle. The particles may then be directed along a beam passage **117** and into the target system **114** so that the particle beam **112** is incident upon the target material **116** located at a corresponding target location **120**. In alternative embodiments, the system **100** may have a target system located within or directly attached to the accelerator chamber **103**.

By way of example, the system **100** may use $^1H^-$ technology and brings the charged particles to a low energy (e.g., about 9.6 MeV) with a beam current of approximately 10-30 μA. In other embodiments, the beam current may be, for example, up to approximately 200 μA or up to 2000 μA or more. Negative hydrogen ions may be accelerated and guided through the particle accelerator **102** and into the extraction system **115**. The negative hydrogen ions may then hit the extraction foil **134** of the extraction system **115** thereby removing the pair of electrons and making the particle a positive ion, $^1H^+$. It is noted, however, embodiments described herein may be applicable to other types of particle accelerators and cyclotrons.

When the particle beam **112** is incident upon the extraction foil **134**, the extraction foil **134** may experience a significant rise in temperature. For example, the extraction foil **134** may experience an increase in temperature of about 750K or more.

Significant temperature changes may cause portions of the extraction foil **134** to expand (or contract) in size. As described in greater detail below, embodiments are configured to permit the extraction foil to change in size and/or move relative to the foil holder so that unwanted stresses sustained by the foil are reduced.

Also shown in FIG. **1**, the system **100** may have multiple target locations **120**A-C where separate target materials **116**A-C are located. A shifting device or system (not shown) may be used to shift the target locations **120**A-C with respect to the particle beam **112** so that the particle beam **112** is incident upon a different target material **116**. A vacuum may be maintained during the shifting process as well. Alternatively, the particle accelerator **102** and the extraction system **115** may not direct the particle beam **112** along only one path, but may direct the particle beam **112** along a unique path for each different target location **120**A-C. Furthermore, the beam passage **117** may be substantially linear from the particle accelerator **102** to the target location **120** or, alternatively, the beam passage **117** may curve or turn at one or more points therealong. For example, magnets positioned alongside the beam passage **117** may be configured to redirect the particle beam **112** along a different path.

The system **100** is configured to produce radioisotopes (also called radionuclides) that may be used in medical imaging, research, and therapy, but also for other applications that are not medically related, such as scientific research or analysis. When used for medical purposes, such as in Nuclear Medicine (NM) imaging or Positron Emission Tomography (PET) imaging, the radioisotopes may also be called tracers. By way of example, the system **100** may generate protons to make $^{18}F^{-}$ isotopes in liquid form, ^{11}C isotopes as CO_2, and ^{13}N isotopes as NH_3. The target material **116** used to make these isotopes may be enriched ^{18}O water, natural $^{14}N_2$ gas, ^{16}O-water. The system **100** may also generate protons or deuterons in order to produce ^{15}O gases (oxygen, carbon dioxide, and carbon monoxide) and ^{15}O labeled water.

The system **100** may also include a control system **118** that may be used by a technician to control the operation of the various systems and components. The control system **118** may include one or more user-interfaces that are located proximate to or remotely from the particle accelerator **102** and the target system **114**. In some embodiments, the control system **118** may be configured to receive data regarding the operability or suitability of the extraction foil **134**. For instance, the control system **118** may inform a use that the extraction foil **134** has failed and that a new extraction foil **134** should be positioned within the path of the charged particles. Such information may be obtained by detecting a current from the extraction foil **134**. In some embodiments, the control system **118** may automatically rotate the foil holder **130** so that a different extraction foil **134** is positioned within the path.

Although not shown in FIG. **1**, the system **100** may also include one or more radiation and/or magnetic shields for the particle accelerator **102** and the target system **114**. The system **100** may include a cooling system **122** that transports a cooling or working fluid to various components of the different systems in order to absorb heat generated by the respective components.

The system **100** may also be configured to accelerate the charged particles to a predetermined energy level. For example, some embodiments described herein accelerate the charged particles to an energy of approximately 18 MeV or less. In other embodiments, the system **100** accelerates the charged particles to an energy of approximately 16.5 MeV or less. In particular embodiments, the system **100** accelerates the charged particles to an energy of approximately 9.6 MeV or less. In more particular embodiments, the system **100** accelerates the charged particles to an energy of approximately 7.8 MeV or less. However, embodiments describe herein may also have an energy above 18 MeV. For example, embodiments may have an energy above 100 MeV, 500 MeV or more.

The system **100** and, more specifically, the particle accelerator **102** may include features described in U.S. application Ser. No. 12/977,208, which is incorporated by reference in its entirety.

FIG. **2** is a perspective view of an extraction device **200** that may be used in a particle accelerator, such as the particle accelerator **102** (FIG. **1**) of the isotope production system **100** (FIG. **1**). The extraction device **200** includes a foil holder **202** and a plurality of extraction foils **204**. The extraction device **200** may also include a holder cover **210** (shown in FIG. **9**). In the illustrated embodiment, the foil holder **202** is configured to hold and position six (6) extraction foils **204** so that charged particles (not shown) from the particle accelerator may be incident upon the corresponding extraction foil **204**. In other embodiments, the foil holder **202** may hold fewer extraction foils (e.g., only one extraction foil) or more extraction foils. The extraction foil **204** may be a substantially rectangular and thin sheet of suitable material, but other shapes may be used in other embodiments. For example, the extraction foil **204** may have a substantially circular profile. The foil material may include carbon and graphite. Typically the foil material is a high melting point, low density material with low radio activation potential, but can be any material capable of sufficiently stripping electrons from the charged particles passing through. By way of example only, the extraction foil may be a carbon/graphite foil having about 1-2 μm thickness.

The foil holder **202** includes a holder body **205** having a plurality of positioning slots **206** that are each sized and shaped to hold one of the extraction foils **204**. The foil holder **202** may also include fasteners or other components and, in some embodiments, the extraction foils **204**. In one or more embodiments, the positioning slots **206** are dimensioned to permit the extraction foils **204** to freely expand or contract within the positioning slot **206**. The positioning slots **206** may be defined by interior reference surfaces (described below) that retain the extraction foils while also permitting edge portions of the extraction foils **204** to move relative to the reference surfaces.

For example, the holder body **205** may include body portions **211**-**213**, including first and second plate portions **211**, **213** and an intermediate portion **212** disposed between the plate portions **211**, **213**. In the illustrated embodiment, the holder body **205** is a single continuous piece of material. For example, the plate portions **211**, **213** and the intermediate portion **212** may be molded and shaped from a common piece of material (e.g., graphite) to include the features described herein. In alternative embodiments, however, one or more of the plate portions **211**, **213** or the intermediate portion **212** may be separate from the others. For example, each of the plate portions **211**, **213** and the intermediate portion **212** may be a separate component that is secured to the other components to form the holder body **205**.

In the illustrated embodiment, the foil holder **202** is configured to be rotated about an axis of rotation **208** to different designated rotational positions. As such, the plate portions **211**, **213** and the intermediate portion **212** may have substantially circular cross-sections taken transverse to the axis of rotation **208**. The plate portions **211**, **213** may be referred to as discs in some embodiments. However, in other embodiments, the foil holder **202** or the body portions **211**-**213** are only partially circular (e.g., semi-circular). For example, instead of having circular cross-sections and being configured to hold six (6) extraction foils **204**, the body portions **211-213** may have semi-circular cross-sections that are configured to hold only three (3) or four (4) extraction foils **204**.

The holder body **205** includes a beam-receiving channel **216** that extends around the axis of rotation **208**. The beam-receiving channel **216** is defined by the plate portions **211**, **213** and the intermediate portion **212**. As shown, the beam-receiving channel **216** opens radially outward from the axis of rotation **208** such that the beam-receiving channel **216** is open-sided. The beam-receiving channel **216** is defined by an exterior channel surface **218**. The channel surface **218** extends along the plate portions **211**, **213** and the intermediate portion **212**. As shown in FIG. **2**, the positioning slots **206** are formed within the channel surface **218**.

In the illustrated embodiment, the channel surface **218** is a single continuous surface that extends from a radial edge **214** of the plate portion **211** along the intermediate portion **212** to a radial edge **215** of the plate portion **213**. For embodiments in which the body portions **211-213** are separate components, however, the channel surface **218** may be collectively formed by separate surfaces of the components. Accordingly, the term "channel surface" may describe a single continuous surface that defines the beam-receiving channel **216** or multiple surfaces that collectively define the beam-receiving channel **216**.

As shown in FIG. **2**, the plate portion **211** may include a plurality of elongated slot openings **222**. The slot openings **222** provide access to corresponding positioning slots **206**. For example, as shown in FIG. **2**, a tool **224** (e.g., pliers) may be used to insert the extraction foils **204** through the slot openings **222** and into the respective positioning slots **206**. As the extraction foils **204** are advanced through the positioning slots **206**, the extraction foil **204** advances across the beam-receiving channel **216**. After the extraction foil **204** has been inserted into the positioning slot **206**, the extraction foil **204** is disposed transverse to the beam-receiving channel **216** such that the extraction foil **204** separates or divides the beam-receiving channel **216**. Once the desired number of extraction foils **204** have been positioned within the holder body **205**, the holder cover **210** (shown in FIG. **9**) may be mounted to the plate portion **211** thereby covering the slot openings **222** so that the extraction foils **204** are confined within the positioning slot **206**.

FIG. **3** illustrates an exemplary extraction foil **204** that may be used by embodiments described herein. In FIG. **3**, dimensions of the extraction foil **204** have been modified for illustrative purposes. Nonetheless, it is understood that embodiments may be selectively configured to utilize an extraction foil having predetermined dimensions or to utilize various types of extraction foils. As shown, the extraction foil **204** includes opposite side surfaces **230**, **232** and foil edges **233-236** that extend between the opposite side surfaces **230**, **232**. In FIG. **3**, the side surfaces **230**, **232** are shown as being substantially planar and the foil edges **233-236** are shown as being substantially linear. It is understood, however, that extraction foils may readily yield (e.g., bend) when external forces are applied and may be shaped to have various contours. The foil edges **233-236** extend along a perimeter of the extraction foil **204** and may define a profile of the extraction foil **204** when the extraction foil **204** is substantially planar. The profile in FIG. **3** is substantially rectangular, but the extraction foil **204** may have other profiles in other embodiments.

As shown, the extraction foil **204** includes an edge portion **238** that extends around the perimeter of the extraction foil

204. The edge portion **238** is defined between the broken line and the foil edges **233-236** in FIG. **3**. The edge portion **238** includes the foil edges **233-236** and also a portion of the side surfaces **230**, **232**. The edge portion **238** may include at least one covered segment and at least one exposed segment. For example, the edge portion **238** includes covered segments **243-245** which extends along and includes the foil edges **233-235**, respectively. The covered segments **243-245** may collectively form a C shape. The edge portion **238** also includes an exposed segment **246** that extends along and includes at least a portion of the foil edge **236**.

In the illustrated embodiment, the edge portion **238** surrounds a body portion **242** of the extraction foil **204**. When the extraction foil **204** is retained with the corresponding positioning slot **206** (FIG. **2**), the body portion **242** and the exposed segment **246** of the edge portion **238** are exposed. For example, the body portion **242** and the exposed segment **246** are not covered by the holder body **205** (FIG. **2**) and are capable of directly receiving charged particles (not shown). Also shown in FIG. **3**, the extraction foil **204** may have a height or thickness **253** that extends between the side surfaces **230**, **232**. The extraction foil **204** also has a length **255** and a width **251** (shown in FIG. **6**).

FIG. **4** is a cross-section of a portion of the holder body **205** taken along the lines **4-4** in FIG. **2**. More specifically, the cross-section is taken through one of the positioning slots **206**. The positioning slot **206** extends around and partially defines a section of the beam-receiving channel **216**. The illustrated section may be referred to as a beam window **240**. The beam window **240** is a planar portion (e.g., slice) of the beam-receiving channel **216** that is configured to be positioned within a path of the particle beam (not shown) when the extraction foil **204** (FIG. **2**) is held within the positioning slot **206**. More specifically, the beam window **240** and the extraction foil **204** are configured to extend orthogonal to a path direction of the particle beam so that the charged particles are incident on the extraction foil **204**.

The positioning slot **206** may constitute a void (e.g., cutout, recess, cavity, and the like) of the holder body **205** that extends a depth into the holder body **205** from the channel surface **218** and extends longitudinally around the beam window **240**. Dimensions of the positioning slot **206** may be configured to retain the extraction foil **204** within the positioning slot **206** during operation of the particle accelerator. As used herein, the term "retained" includes holding the extraction foil **204** in a designated position relative to the holder body **205**. In some embodiments, the extraction foil **204** may be retained within the positioning slot **206** without compressive forces (e.g., without clamping or pinching) sustained by the extraction foil **204**. For instance, the extraction foil **204** may rest within the positioning slot **206** such that the only force experienced by the extraction foil **204** is gravity and incidental frictional forces between the extraction foil **204** and interior reference surfaces that define the positioning slot **206**. In some embodiments, the extraction foil **204** may rest within the positioning slot **206** without resins or adhesives coupling the extraction foil **204** to the reference surfaces. Alternatively, resins or adhesives that permit the extraction foil to move within the positioning slot **206** may be used.

In one embodiment, the positioning slot **206** is defined by interior reference surfaces **261-265** and an interior reference surface **266** (shown in FIG. **4**). The reference surfaces **261-266** are surfaces of the holder body **205** and may be formed when, for example, the holder body **205** (or components thereof) are molded and/or shaped. In some embodiments, the material of the holder body **205** may be graphite. Unlike clamps that may be used in conventional systems, the reference surfaces **261-266** are not moveable with respect to each other in other embodiments. In some embodiments, however, one or more of the reference surfaces **261-266** may be moveable relative to the other reference surfaces. For example, one or more portions of the holder body **205** may be removed to position the extraction foil **204**.

As shown, the positioning slot **206** opens to the channel surface **218**. The channel surface **218** along the positioning slot **206** may extend around and at least partially define a perimeter or profile of the beam window **240**. For example, in the illustrated embodiment, a majority of the beam window **240** is framed by the channel surface **218** that extends along the positioning slot **206**. More specifically, the beam window **240** is framed by slot edges **272-274** defined between the channel surface **218** and the reference surface **265**. More specifically, the slot edges **272-274** are defined where the channel surface **218** joins or intersects with the reference surface **265**. Although not shown, the positioning slot **206** may also be defined by slot edges that are formed where the channel surface **218** joins or intersects the reference surface **265**. The positioning slot **206** or, more specifically, the channel surface **218** along the positioning slot **206** may be C-shaped or L-shaped in some embodiments. Also shown, the beam window **240** or the beam-receiving channel **216** includes an open side **270**.

The reference surfaces **261-266** are configured to face the extraction foil **204** when the extraction foil **204** is disposed within and retained by the positioning slot **206**. More specifically, the reference surfaces **265** and **266** may face each other and the side surfaces **230**, **232** (FIG. **3**), respectively, when the extraction foil **204** is disposed within the positioning slot **206**. As such, the reference surfaces **265**, **266** may be referred to as broadside-reference surfaces. The reference surface **263** may face the foil edge **234** (FIG. **3**), the reference surface **262** may face the foil edge **233** (FIG. **3**), and the reference surfaces **261** and **264** may face the foil edge **236** (FIG. **3**). As such, the reference surfaces **261-264** may be referred to as edge-reference surfaces. When the extraction foil **204** is retained within the positioning slot **206**, at least one of the reference surfaces **261-266** may directly engage the extraction foil **204**. Also shown in FIG. **4**, the slot opening **222** provides access to the positioning slot **206**. More specifically, the plate portion **211** includes an outer surface **278** that includes the slot opening **222**.

FIG. **5** is an enlarged view of the slot opening **222** along the outer surface **278** of the plate portion **211**. The slot opening **222** may be sized and shaped to receive a width **251** (shown in FIG. **6**) and the thickness **253** (FIG. **3**) of the extraction foil **204**. For example, the slot opening **222** has a width **280** and a height **282**. The height **282** of the slot opening **222** is defined between the opposing reference surfaces **265**, **266**, and the width **280** is defined between the opposing reference surfaces **263**, **264**. In the illustrated embodiment, the dimensions of the positioning slot **206** (FIG. **2**) are substantially uniform. More specifically, the positioning slot **206** may also have the height **282** and the width **280** uniformly throughout. In other embodiments, however, dimensions of the positioning slot **206** may vary.

FIG. **6** is a cross-section of a portion of the extraction device **200** that illustrates the extraction foil **204** retained within the positioning slot **206** of the foil holder **202**. For illustrative purposes, the extraction foil **204** is indicated by broken lines. As shown, the holder cover **210** is mounted to the holder body **205** along the outer surface **278** thereby covering the slot opening **222** to the positioning slot **206**. In the embodiment shown in FIG. **6**, the reference surface **261** faces the foil edge **236**; the reference surface **262** faces the foil edge **233**; the reference surface **263** faces the foil edge **234**; the reference surface **264** faces the foil edge **236**; the reference surface **265** faces the side surface **230** (FIG. **3**); and, as shown in FIG. **8**, the reference surface **266** faces the side surface **232**. It is noted that the locations of the foil edges **233-236** within the positioning slot **206** are for illustration only and that the foil edges **233-236** may have other locations in other embodiments. For example, the foil edge **235** may be closer to or further away from the holder cover **210**.

Depending upon the location of the extraction foil **204** within the positioning slot **206** and the contour of the extraction foil **204**, one or more of the reference surfaces **261-266** may directly engage the portion of the extraction foil **204** that the corresponding reference surface faces. For example, the foil edge **233** and the reference surface **262** are directly engaging each other in FIG. **6**. The holder body **205** may be oriented such that gravity causes the foil edge **233** to rest upon the reference surface **262**. However, FIG. **6** illustrates just one example and the extraction foil **204** may engage other reference surfaces that define the positioning slot **206**.

As shown in FIG. **6**, the body portion **242** and the exposed segment **246** are exposed within the beam window **240**. In the illustrated embodiment, the exposed segment **246** is defined between the opposing slot edges **272**, **274** along the channel surface **218**. However, in alternative embodiments, the extraction foil **204** may clear one or more of the radial edges **214**, **215** such that the exposed segment **246** is not located within the portion of the beam window **240** defined between the slot edges **272**, **274**.

As shown, a beam spot **286** is located along the exposed segment **246** and the body portion **242**. The beam spot **286** represents a cross-section of the particle beam (not shown) when incident on the extraction foil **204**. The extraction foil **204** extends substantially orthogonal (perpendicular) to the path taken by the charged particles. During operation of the particle accelerator, the particle beam may be incident upon the extraction foil **204** at the beam spot **286**. Thermal energy generated at the beam spot **286** may be conveyed to other portions of the extraction foil **204**. Portions of the extraction foil **204** that experience an increase in thermal energy may expand (or contract). The amount of expansion and/or contraction may be based on a coefficient of thermal expansion for the material of the extraction foil **204**. As such, at least one of a size or shape of the extraction foil **204** may change during operation of the particle accelerator. Nonetheless, the positioning slot **206** is dimensioned by the reference surfaces **261-266** to hold the extraction foil **204** such that the extraction foil **204** or, more specifically, the portion of the extraction foil **204** that directly receives the charged particles, substantially maintains a designated position relative to the particle beam. As such, the positioning slot **206** may be dimensioned to permit movement of the extraction foil **204** while substantially maintaining a position of the extraction foil **204**.

FIGS. **7** and **8** illustrate movement of the extraction foil **204** within the positioning slot **206**. One or more portions of the extraction foil **204** may move relative to the reference surfaces **261-266** (FIG. **3**) when the charged particles generate thermal energy within the extraction foil **204**. As shown in FIG. **7**, the covered segment **245** of the edge portion **238** may move relative to the reference surfaces **263-265**. The covered segment **245** may also move relative to the reference surface **266** (FIG. **8**). For example, if the extraction foil **204** is expanding, the foil edge **235** may extend or move closer to the outer surface **278** of the holder body **205** or may move further from the slot edge **274** as indicated by the arrows in FIG. **7**. As shown in FIG. **8**, the side surfaces **230**, **232** may move with respect to the reference surfaces **265**, **266**. For example, the side surfaces **230**, **232** may move away from the reference surface **265** and closer to the reference surface **266**. It is noted that the location of foil edge **235** is to illustrate movement of the extraction foil **204** only. Depending upon the configuration of the positioning slot **206**, the foil edge **235** may be closer to or further from the holder cover **210**.

FIG. **9** is a perspective view of the extraction device **200** in which the holder cover **210** has been mounted to the foil holder **202** or the holder body **205**. More specifically, the holder cover **210** is mounted onto the outer surface **278** (FIG. **4**) of the holder body **205** thereby covering the slot openings **222** (FIG. **2**). In some embodiments, the extraction foils **204** may be disposed entirely within the positioning slots **206**. However, in other embodiments, the extraction foils **204**, when resting within the positioning slots **206**, may clear the outer surface **278** such that a portion of the extraction foil **204** is located between the holder cover **210** and the holder body **205**.

In some embodiments, the holder cover **210** also has a substantially circular cross-section when viewed along the axis of rotation **208**. The holder cover **210** includes a radial edge **288**. In the illustrated embodiment, the holder cover **210** has a diameter that is greater than a diameter of the plate portion **211** (FIG. **2**) such that the radial edge **288** clears and is located beyond the radial edge **214** (FIG. **2**). The holder cover **210** may include recesses or notches **290** along the radial edge **214**. The recesses **290** may facilitate gripping the holder cover **210** during an installation or removal process. Also shown, the holder cover **210** may be secured to the holder body **205** using one or more fasteners **292**, which are illustrated as screws in FIG. **9**. However, other types of fasteners may be used in alternative embodiments.

As shown, the foil holder **202** includes a bore **294** that is configured to receive a shaft or rod (not shown) that is operably attached to a rotating motor (not shown). The rotating motor may be similar to the rotating motor **132** (FIG. **1**). The rotating motor is configured to rotate the shaft thereby rotating the foil holder **202**. In this manner, the foil holder **202** may be selectively rotated to designated orientations in order to position an extraction foil **204** within a path of the charged particles. In some embodiments, the foil holder **202** is configured to be shifted in a direction that is orthogonal to the axis of rotation **208**. For example, the shaft may be shifted so that the extraction foils **204** are effectively moved to different positions without rotating the shaft.

FIG. **10** is a flowchart illustrating a method **300** of operating a particle accelerator in accordance with one embodiment. The method **300**, for example, may employ structures or aspects of various embodiments (e.g., systems and/or methods) discussed herein. In various embodiments, certain steps may be omitted or added, certain steps may be combined, certain steps may be performed simultaneously, certain steps may be performed concurrently, certain steps may be split into multiple steps, certain steps may be performed in a different order, or certain steps or series of steps may be re-performed in an iterative fashion.

The method **300** may include inserting (at **302**) an extraction foil within a positioning slot. The inserting (at **302**) may include inserting an edge of the extraction foil through a slot opening that provides access to the positioning slot, such as the slot opening **222** and the positioning slot **206** described above. The method **300** also includes retaining (at **304**) the extraction foil within the positioning slot. The retaining operation may be accomplished by the dimensions of the positioning slot. More specifically, the dimensions of the positioning slot may be configured to at least slightly exceed a thickness of the extraction foil and a width of the extraction foil. In this manner, the extraction foil may slide along or proximate to reference surfaces that define the positioning slot during the positioning operation. Moreover, the dimensions of the positioning slot may permit at least some movement of the extraction foil while substantially maintaining a designated position or orientation of the extraction foil. In particular embodiments, the extraction foil is not secured in a fixed position by clamping or other compressive forces.

When the extraction foil is located within the positioning slot, the reference surfaces may face the extraction foil and one or more of the reference surfaces may directly engage the extraction foil. For example, the extraction foil may have at least one edge portion that defines a profile of the extraction foil and a body portion that is exposed for receiving a particle beam. The edge portion may directly engage one or more of the reference surfaces.

The method **300** may also include directing (at **306**) a particle beam to be incident upon the extraction foil. When the charged particles hit the extraction foil, electrons from the extraction foil may be removed. In some embodiments, the electrons may accumulate to form a current that is transmitted through the holder body that defines the positioning slot. Concurrently, the charged particles may generate thermal energy (heat) within the extraction foil. Due to the dimensions of the positioning slot, the thermal energy may cause the extraction foil to move therein (e.g., through expansion or contraction). For example, the edge portion of the extraction foil may be permitted to move relative to the reference surfaces. In some cases, the edge portion of the extraction foil moves relative to the reference surfaces when thermal energy causes the extraction foil to change in at least one of size or shape.

In some embodiments, the foil holder may include multiple positioning slots. As such, the method **300** may also include moving (at **308**) the foil holder to position a different extraction foil within a path of the particle beam. For example, the foil holder may be rotated about an axis of rotation to position the other extraction foil.

In particular embodiments, the particle accelerators and cyclotrons are sized, shaped, and configured for use in hospitals or other similar settings to produce radioisotopes for medical imaging. However, embodiments described herein are not intended to be limited to generating radioisotopes for medical uses. Furthermore, in the illustrated embodiments, the particle accelerators are vertically-oriented isochronous cyclotrons. However, alternative embodiments may include other kinds of cyclotrons or particle accelerators and other orientations (e.g., horizontal).

In one embodiment, a particle accelerator is provided that may include an electrical field system and a magnetic field system configured to direct a particle beam of charged particles along a designated path within an acceleration chamber. The particle accelerator may include a foil holder having a beam window and a positioning slot that at least partially surrounds the beam window. The positioning slot is dimensioned to hold an extraction foil such that the extraction foil extends across the beam window and into the path of the charged particles. The positioning slot is defined by interior reference surfaces that face the extraction foil and retain the extraction foil within the positioning slot. The reference surfaces permit the extraction foil to move relative to the reference surfaces when the particle beam is incident on the extraction foil.

In one aspect, the positioning slot may only partially surround the beam window such that an edge of the extraction foil is exposed within or proximate to the beam window.

In another aspect, the positioning slot may be substantially C-shaped or L-shaped as the positioning slot at least partially surrounds the beam window.

In another aspect, at least three of the references surfaces may have fixed positions with respect to one another. For example, the at least three reference surfaces may include first, second, and third reference surfaces. The first and second reference surfaces may directly oppose each other and be configured to face opposite side surfaces of the extraction foil. The third reference surface may be configured to face an edge of the extraction foil.

In another aspect, the foil holder may include a holder body having an outer surface that faces away from the positioning slot. The foil holder has an elongated slot opening along the outer surface that is shaped to receive the extraction foil. The slot opening provides access to the positioning slot.

In another aspect, the foil holder may include a holder body that defines a beam-receiving channel that curves about an axis of rotation. The foil holder may be configured to rotate about the axis of rotation.

In another aspect, the foil holder may include a plurality of the positioning slots that are each configured to hold a corresponding extraction foil.

In another embodiment, an extraction system for removing electrons from charged particles is provided. The extraction system may include a foil holder that has a beam window and a positioning slot that at least partially surrounds the beam window. The positioning slot may be dimensioned to hold an extraction foil such that the extraction foil extends across the beam window. The positioning slot may be defined by interior reference surfaces that face the extraction foil and retain the extraction foil within the positioning slot. The reference surfaces may be dimensioned to permit the extraction foil to move relative to the reference surfaces when the charged particles are incident on the extraction foil.

In one aspect, the positioning slot may only partially surround the beam window such that an edge of the extraction foil is exposed within or proximate to the beam window.

In another aspect, at least three of the references surfaces may have fixed positions with respect to one another.

In another aspect, the foil holder may include a holder body having an outer surface that faces away from the positioning slot. The foil holder has an elongated slot opening along the outer surface that is shaped to receive the extraction foil. The slot opening provides access to the positioning slot.

In another aspect, the foil holder may be configured to be rotated about an axis of rotation. The foil holder may include a plurality of the positioning slots that are each configured to hold a corresponding extraction foil. Each of the positioning slots may extend radially away from the axis of rotation.

In another aspect, the extraction system includes the extraction foil, wherein more than half of a perimeter of the extraction foil is covered by the foil holder.

In another embodiment, a method of operating a particle accelerator is provided. The method may include positioning an extraction foil within a positioning slot. The extraction foil has at least one edge portion that defines a profile of the extraction foil and a body portion that is exposed for receiving a particle beam. The positioning slot may be defined by interior reference surfaces that face the edge portion, wherein at least one of the reference surfaces directly engages the extraction foil. The method may also include directing the particle beam to be incident upon an extraction foil. The edge portion of the extraction foil may be permitted to move relative to the reference surfaces.

In one aspect, positioning the extraction foil within the positioning slot may include permitting the extraction foil to rest within the positioning slot, wherein gravity causes the extraction foil to rest against at least one of the reference surfaces such that the extraction foil is retained within the positioning slot.

In another aspect, the references surfaces may include first and second reference surfaces that oppose each other and face respective side surfaces of the extraction foil. The first and second reference surfaces may be separated by at least a designated distance measured along a thickness of the extraction foil. The designated distance may be greater than the thickness of the extraction foil.

In another aspect, the extraction foil is not secured in a fixed position by clamping.

In another aspect, the positioning slot may be one of a plurality of positioning slots of a foil holder. The method may also include rotating the foil holder to position a different extraction foil within a path of the particle beam.

In another aspect, the extraction foil is substantially rectangular and the edge portion includes at least two covered edge portions and at least one exposed edge portion. The covered edge portions may be disposed within the positioning slot.

It is to be understood that the above description is intended to be illustrative, and not restrictive. For example, the above-described embodiments (and/or aspects thereof) may be used in combination with each other. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from its scope. While the dimensions and types of materials described herein are intended to define the parameters of the invention, they are by no means limiting and are exemplary embodiments. Many other embodiments will be apparent to those of skill in the art upon reviewing the above description. The scope of the invention should, therefore, be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled. In the appended claims, the terms "including" and "in which" are used as the plain-English equivalents of the respective terms "comprising" and "wherein." Moreover, in the following claims, the terms "first," "second," and "third," etc. are used merely as labels, and are not intended to impose numerical requirements on their objects. Further, the limitations of the following claims are not written in means-plus-function format and are not intended to be interpreted based on 35 U.S.C. §112, sixth paragraph, unless and until such claim limitations expressly use the phrase "means for" followed by a statement of function void of further structure.

This written description uses examples to disclose the invention, including the best mode, and also to enable any person skilled in the art to practice the invention, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal languages of the claims.

What is claimed is:

1. A particle accelerator comprising:

an electrical field system and a magnetic field system configured to direct a particle beam of charged particles along a designated path within an acceleration chamber; and

a foil holder having a beam window and a positioning slot that at least partially surrounds the beam window, the positioning slot dimensioned to hold an extraction foil such that the extraction foil extends across the beam window and into the path of the charged particles, the positioning slot being defined by interior reference surfaces that face the extraction foil and retain the extraction foil within the positioning slot, the reference surfaces permitting the extraction foil to move relative to the reference surfaces when the particle beam is incident on the extraction foil.

2. The particle accelerator of claim **1**, wherein the positioning slot only partially surrounds the beam window such that an edge of the extraction foil is exposed within or proximate to the beam window.

3. The particle accelerator of claim **2**, wherein the positioning slot is substantially C-shaped or L-shaped as the positioning slot at least partially surrounds the beam window.

4. The particle accelerator of claim **1**, wherein at least three of the references surfaces have fixed positions with respect to one another.

5. The particle accelerator of claim **4**, wherein the at least three reference surfaces include first, second, and third reference surfaces, the first and second reference surfaces directly opposing each other and configured to face opposite side surfaces of the extraction foil, the third reference surface configured to face an edge of the extraction foil.

6. The particle accelerator of claim **1**, wherein the foil holder includes a holder body having an outer surface that faces away from the positioning slot, the foil holder having an elongated slot opening along the outer surface that is shaped to receive the extraction foil, the slot opening providing access to the positioning slot.

7. The particle accelerator of claim **1**, wherein the foil holder includes a holder body that defines a beam-receiving channel that curves about an axis of rotation, the foil holder configured to rotate about the axis of rotation.

8. The particle accelerator of claim **1**, wherein the foil holder includes a plurality of the positioning slots that are each configured to hold a corresponding extraction foil.

9. An extraction system for removing electrons from charged particles, the extraction system comprising a foil holder that includes a beam window and a positioning slot that at least partially surrounds the beam window, the positioning slot dimensioned to hold an extraction foil such that the extraction foil extends across the beam window, the positioning slot being defined by interior reference surfaces that face the extraction foil and retain the extraction foil within the positioning slot, the reference surfaces dimensioned to permit the extraction foil to move relative to the reference surfaces when the charged particles are incident on the extraction foil.

10. The extraction system of claim **9**, wherein the positioning slot only partially surrounds the beam window such that an edge of the extraction foil is exposed within or proximate to the beam window.

11. The extraction system of claim **9**, wherein at least three of the references surfaces have fixed positions with respect to one another.

12. The extraction system of claim **9**, wherein the foil holder includes a holder body having an outer surface that faces away from the positioning slot, the foil holder having an elongated slot opening along the outer surface that is shaped to receive the extraction foil, the slot opening providing access to the positioning slot.

13. The extraction system of claim **9**, wherein the foil holder is configured to be rotated about an axis of rotation, the foil holder including a plurality of the positioning slots that are each configured to hold a corresponding extraction foil, each of the positioning slots extending radially away from the axis of rotation.

14. The extraction system of claim **9**, further comprising the extraction foil, wherein more than half of a perimeter of the extraction foil is covered by the foil holder.

15. A method of operating a particle accelerator, the method comprising:

positioning an extraction foil within a positioning slot, the extraction foil having at least one edge portion that defines a profile of the extraction foil and a body portion that is exposed for receiving a particle beam, the positioning slot being defined by interior reference surfaces that face the edge portion wherein at least one of the reference surfaces directly engages the extraction foil; and

directing the particle beam to be incident upon an extraction foil, wherein the edge portion of the extraction foil is permitted to move relative to the reference surfaces.

16. The method of claim **15**, wherein positioning the extraction foil within the positioning slot includes permitting the extraction foil to rest within the positioning slot, wherein gravity causes the extraction foil to rest against at least one of the reference surfaces such that the extraction foil is retained within the positioning slot.

17. The method of claim **15**, wherein the references surfaces include first and second reference surfaces that oppose each other and face respective side surfaces of the extraction foil, the first and second reference surfaces being separated by at least a designated distance measured along a thickness of the extraction foil, the designated distance being greater than the thickness of the extraction foil.

18. The method of claim **15**, wherein the extraction foil is not secured in a fixed position by clamping.

19. The method of claim **15**, wherein the positioning slot is one of a plurality of positioning slots of a foil holder, the method further comprising rotating the foil holder to position a different extraction foil within a path of the particle beam.

20. The method of claim **15**, wherein the extraction foil is substantially rectangular and the edge portion includes at least two covered edge portions and at least one exposed edge portion, the covered edge portions being disposed within the positioning slot.

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